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Extra-Tropical Cyclones in a Warming Climate: Observational Evidence of Trends in Frequencies and Intensities in the North Pacific, North Atlantic, and Great Lakes Regions

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1. INTRODUCTION AND OVERVIEW

Extra-Tropical Cyclone (ETC) is a generic term for any non-tropical, synoptic-scale, low pressure storm system that develops along a boundary between warm and cold air masses. The extra-tropical types of cyclonic storms are baroclinic, in that they derive their energy from lateral gradients in temperature and pressure. They are the dominant weather phenomenon occurring in the mid- and high-latitudes during the cold season, and are typically large and often have severe weather associated with them. ETCs also generate high-amplitude surface waves over the oceans, and therefore play an important role in forcing and modulating the open ocean wave climate and have severe impacts along coasts.

Most previous studies of changes in ETCs and associated frontal systems have focused on cyclogenesis locations, and the resulting storm tracks, frequencies, and intensities, as well as their coastal impacts. The primary constraint on these studies has been the limited period of record available that has the best observational coverage for reanalysis efforts and verification of results, with most research focused on the latter half of the 20th century. In addition to those studies using reanalysis data, other studies of the variability of storms and long-term changes have typically used wave or water level measurements as proxies for storm frequency and intensity.

In this paper we will present a review of the observational evidence for trends in the frequency and intensity of ETCs in the Northern Hemisphere, and specifically in the North Pacific and North Atlantic basins, as well as in the Great Lakes region. In addition, analysis of changes in significant wave heights (*Hs,* the average of the highest 1/3 of the waves) at NOAA buoys off the Atlantic coast of the U.S. will give supporting evidence for the observed changes in ETC characteristics, and a northward shift in storm tracks.

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2. CHANGES IN STORM TRACKS AND ETC CHARACTERISTICS IN THE ATMOSPHERE

Numerous recent studies have investigated changes in Northern Hemisphere storm track activity and specifically changes in storm frequency and intensity due to warming surface and tropospheric temperatures. A significant pole-ward shift of the storm track in both the North Pacific and North Atlantic Oceans has been verified by a number of recent studies that have shown a decrease in ETC frequency in mid-latitudes, and a corresponding increase in ETC activity in high-latitudes (e.g., Wang et al. 2006a; Zhang et al. 2004; Simmonds and Keay 2002; Paciorek et al. 2002; Graham and Diaz 2001; Geng and Sugi 2001; McCabe et al. 2001; Key and Chan 1999; Serreze et al. 1997). Several of these studies have examined changes in storm tracks over the entire Northern Hemisphere (McCabe et al. 2001; Paciorek et al. 2002; Key and Chan 1999), while others have focused on the storm track changes over the Pacific (Graham and Diaz 2001) or Atlantic basins (Geng and Sugi 2001), or both (Wang and Swail 2001).

Most previous studies have focused on changes in frequency and intensity observed during winter (DJF) or the entire cold season (Nov-Mar). However, for spring, summer and autumn, Key and Chan (1999) found opposite trends in 1000-hPa and 500-hPa cyclone frequencies for both the mid- and high latitudes of the Northern Hemisphere.

The annual departures of ETC frequency for the entire Northern Hemisphere over the period 1959-1997 (McCabe et al. 2001) illustrates that cyclone frequency has decreased for the mid-latitudes (30-60 N; Fig. 1a) and increased for the high latitudes (60-90 N; Fig. 1b). Northern Hemisphere ETC intensity has increased over the latter half of the 20th century across both the mid- and high-latitudes (Fig. 1c,d; McCabe et al. 2001), with the upward trend more significant for the high latitudes ($\alpha = 0.01$ level) than for the mid-latitudes ($\alpha = 0.10$ level).

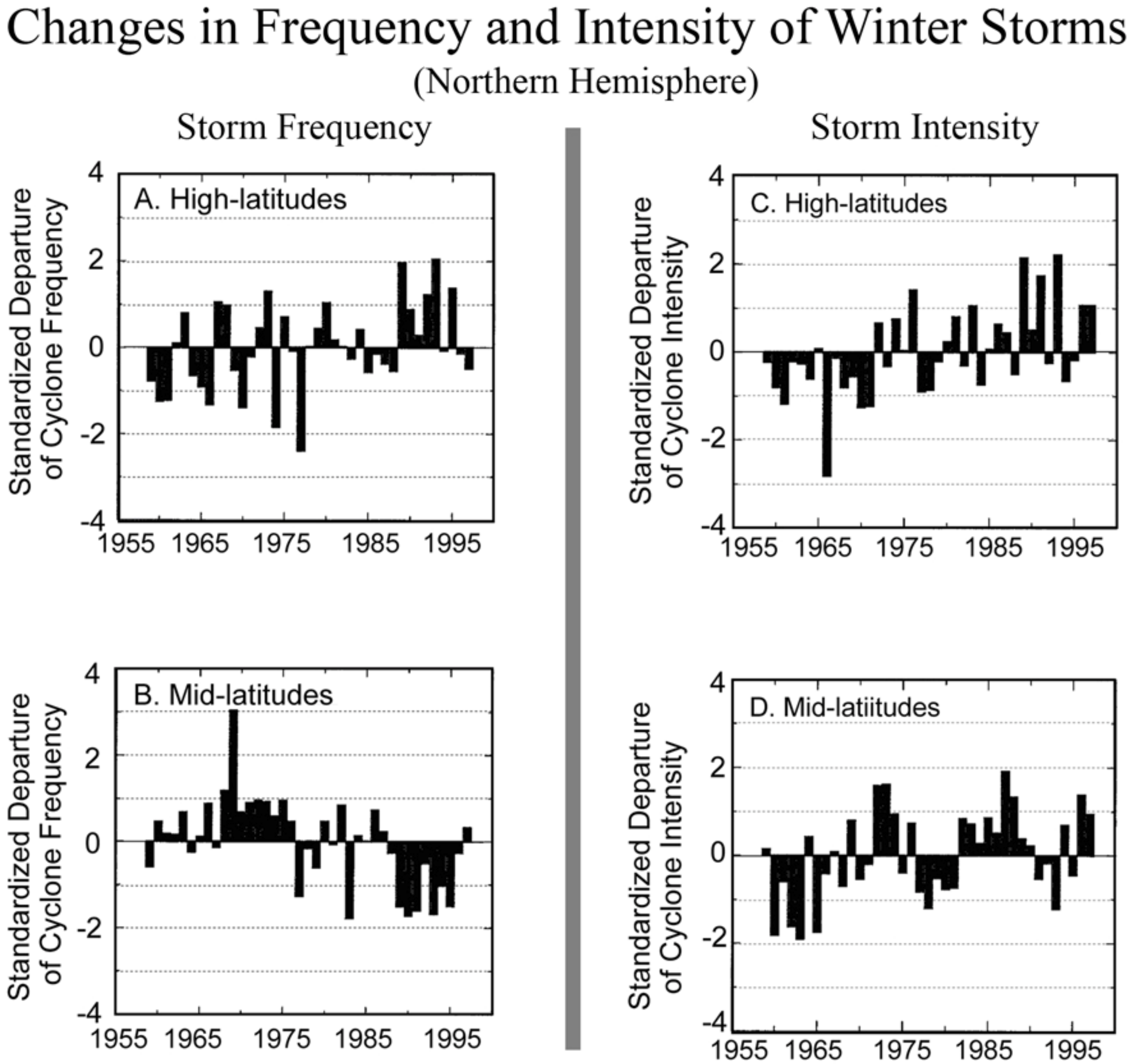

Figure 1. Changes from average (1959-1997) in the number of winter (Nov-Mar) storms each year in the Northern Hemisphere for (a) high latitudes (60-90 N), and (b) mid-latitudes (30-60 N), and the change from average of winter storm intensity in the Northern Hemisphere each year for (c) high latitudes (60-90 N), and (d) mid-latitudes (30-60 N). [Adapted from McCabe et al. 2001].

From an ocean basin perspective, the observed increase in intense ETCs appears to be more robust across the North Pacific than the North Atlantic. Using reanalysis (i.e. model) data covering the period 1949-1999, Paciorek et al. (2002) found that extreme wind speeds (defined as the 95th-percentile of four times daily wind speeds during winter) have increased significantly in both basins (Fig. 2a,d). Their results also showed that the observed upward trend in the frequency of intense cyclones has been more pronounced in the North Pacific basin (Fig. 2c), although the inter-annual variability is much less in the Atlantic (Fig. 2f). Surprisingly, they found that the overall counts of ETCs showed either no long-term change, or a decrease in the total number of cyclones (Fig. 2b,e). However, this was possibly the result of the large latitudinal domain used in their study (20-70 N), which included parts of the tropics, sub-tropics, mid- and high latitudes.

On a regional scale, ETC activity has increased in frequency, duration and intensity in the lower Canadian Arctic during 1953-2002, with the most statistically significant trends during winter (α = 0.05 level; Wang et al. 2006b).

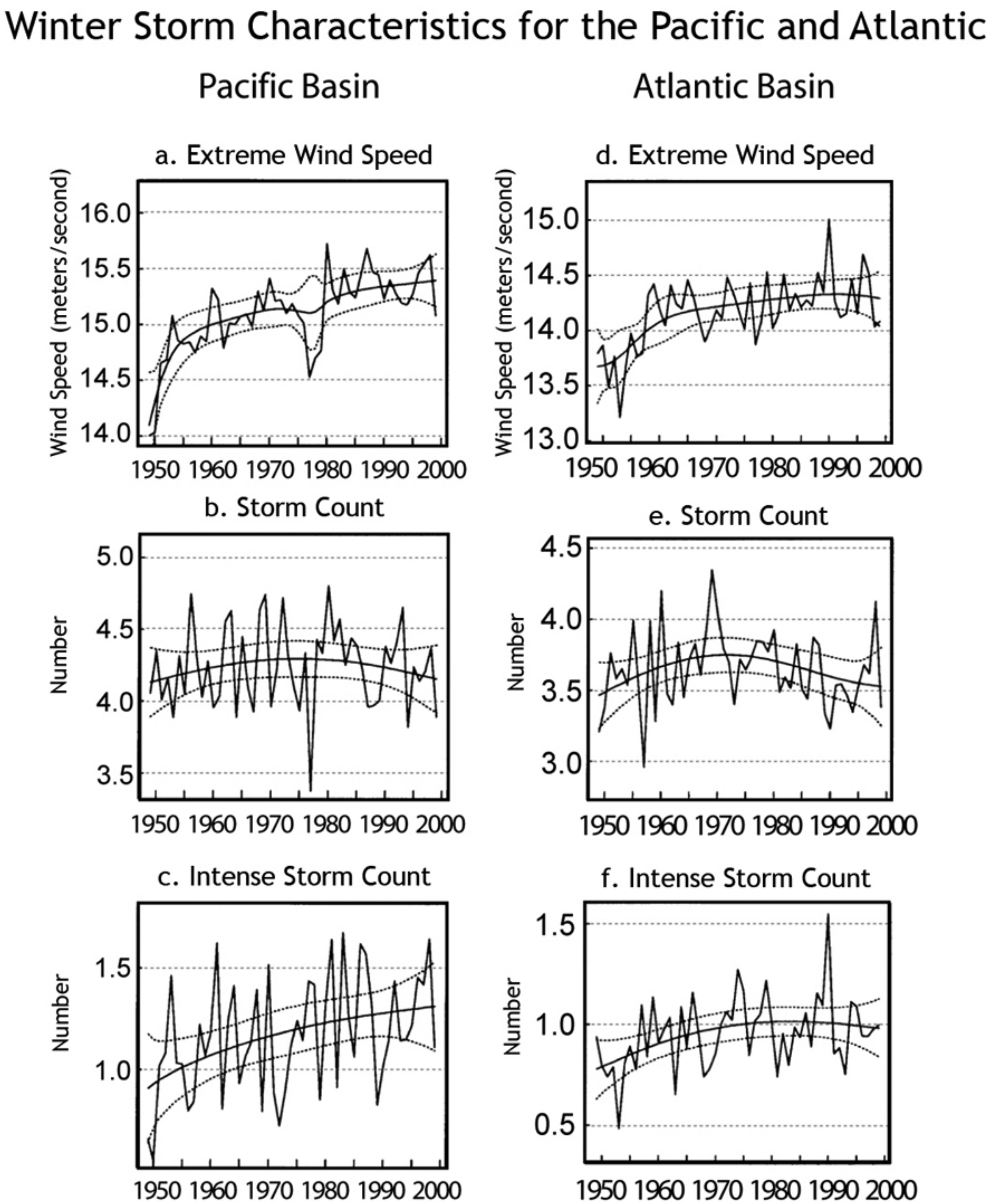

Figure 2. Extreme wind speed (m/s), number of winter storms, and number of intense (≤ 980 hPa) winter storms for the North Pacific region (20-70 N, 130 E-112.5 W; panels a-b-c) and the North Atlantic region (20-70 N, 7.5 E-110 W; panels d-e-f):. The thick smooth lines are the trends determined using a Bayesian spline model, and the thin dashed lines denote the 95% confidence intervals (α = 0.05). [Adapted from Paciorek et al. 2002].

In the southern Prairies-British Columbia region of Canada, winter cyclone deepening rates (i.e. rates of intensification) have increased in the zone around 60 N, but decreased farther south. This is also indicative of a pole-ward shift in ETC activity, and corresponding weakening of ETC's in the mid-latitudes and an increase in the high latitudes (Wang et al. 2006b).

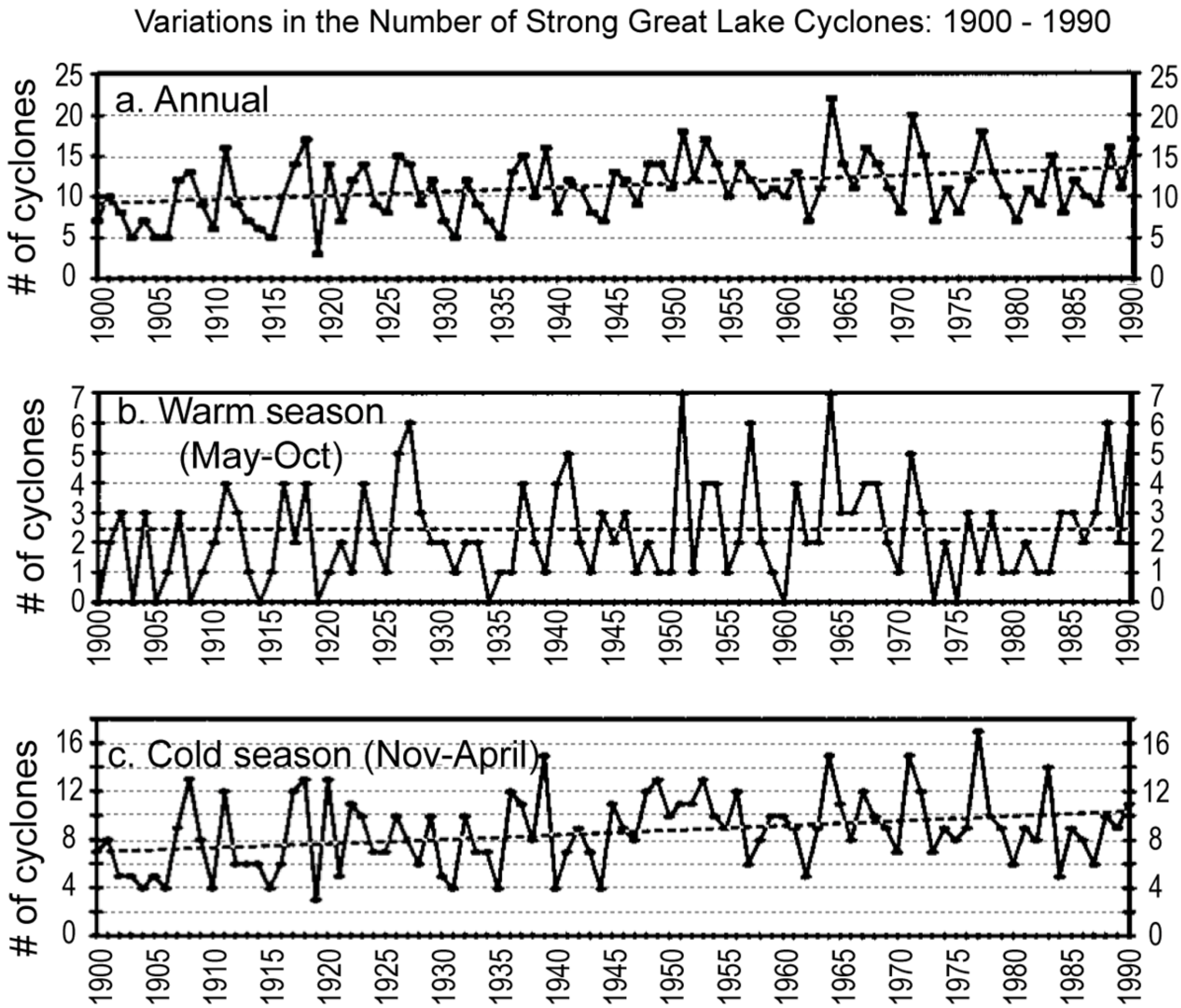

Figure 3. Time series of the number of strong (≤992 hPa) cyclones across the Great Lakes region (40-50 N, 75-93 W) over the period 1900-1990 for (a) Annual, (b) Warm season (May-Oct), and (c) Cold season (Nov-Apr). All trends were significant at the 95% level (α = 0.05). [Adapted from Angel and Isard 1998].

There have been very few studies that have analyzed the climatological frequencies and intensities of ETC's across the central U.S., specifically in the Great Lakes region (e.g., Lewis 1987; Harman et al. 1980; Garriott 1903). Figure 3 shows that over the period 1900 to 1990 the number of strong cyclones (≤992 mb) increased significantly across the Great Lakes (Angel and Isard 1998). Increasing trends have occurred (α = 0.05 level) both annually and during the cold season (Nov-Apr). In fact, over the 91-year period analyzed, it was found that the number of strong cyclones per year more than doubled during both November and December.

3. CHANGES IN SIGNIFICANT WAVE HEIGHTS (*Hs*)

In addition to studies using reanalysis (i.e. model) data, which have records going back to the mid-20th century, other longer-term studies of the variability of *storminess* – which includes the frequency, intensity and duration of storms – typically use wave or water level measurements as proxies for storm frequency and intensity. Specifically, ETC intensity and track location modulate the amplitude and distribution of wave heights and durations measured by ocean buoys. Changes in long period (>12 sec), intermediate period (6-12 sec), and short period (<6 sec) components in the wave-energy spectra permit inferences regarding

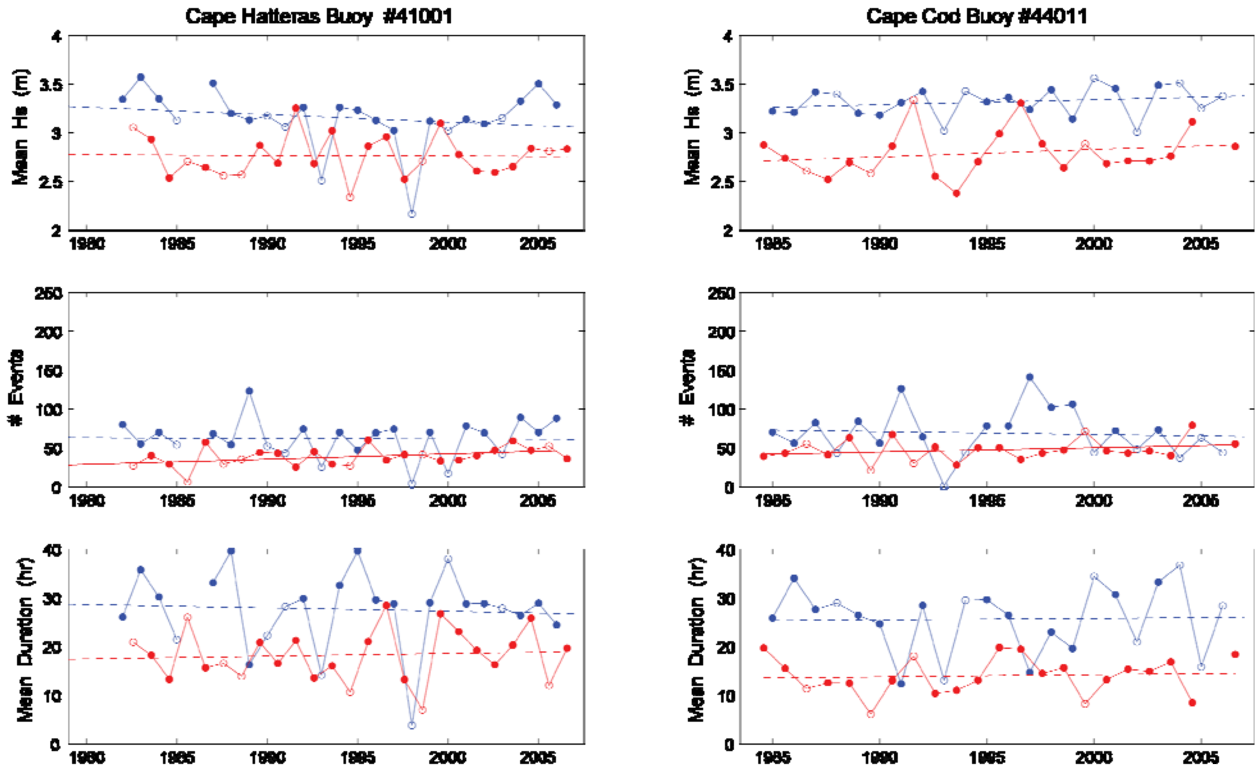

Figure 4. Time series and trends of mean significant wave height (*Hs*), total wave events, and mean wave event duration (hr) for the Cape Hatteras (#41001; left panels) and Cape Cod (#44011; right panels) buoys along the East Coast of the US. The analysis applied a >2m threshold on the wave heights using hourly buoy data from the NOAA National Data Buoy Center (NDBC), where blue represents the cold season (Nov- Mar) and red the warm season (May-Sep). Solid circles denote those years with >75% of observations, while open circles represent years with <75% of available observations. Solid trend lines were significant above the 90% confidence level ($\alpha < 0.1$), while the dashed lines are below the 90% level ($\alpha > 0.1$). Gaps indicate limited or no data were available during those seasons.

the changes over time of the paths of the storms, as well as their intensities and resulting wave energies (Bromirski et al. 2005).

In the eastern North Pacific, analysis of the combination of observations from several buoys off the West Coast of the US supports a progressive northward shift of the dominant North Pacific storm tracks to the central latitudes (Bromirski et al. 2005; not shown). In the western North Atlantic, a northward shift is also inferred from long-term changes in the significant wave height (*Hs*) measured by open ocean buoys. Higher wave heights result from increases in wind speed, storm size, and the duration that higher wind speeds persist. Proximity of the buoy to the storm track is also an important factor in measured Hs. As shown in Figure 4, a decreasing trend in the mean annual *Hs* is evident in the Cape Hatteras buoy time series since the early 1980's during the cold season (Nov – Apr). In contrast, the mean annual *Hs* has increased over the past two decades farther north at buoy 44011 off Cape Cod.

Although the results of the buoy *Hs* analysis are not definitive due to the sparse spatial sampling of the ocean gravity wave field and data gaps, they are in agreement with the observed changes in ETCs based on the reanalysis studies. In addition, the trends in the buoy measurements were not significant above the 90% ($\alpha = 0.1$) confidence level. It should be noted that there are several possible causes for the observed *Hs* increase off Cape Cod. The most likely cause is increasing surface winds to the north (i.e. increasing storm intensity), along with a concomitant decrease in the south. However, a shift in storm track to the north (or eastward) is another possibility for the observed changes in *Hs* along the East Coast of the U.S.

4. SUMMARY

A northward shift in the mid-latitude storm track is supported by studies of reanalysis atmospheric data and buoy wave measurements along the West and East coasts of the North America. In addition to a northward shift, several recent studies have identified an increase in intensity of ETCs in the North Pacific and North Atlantic basins during the cold season. Over the Great Lakes region, analysis of station pressure data has revealed a long-term trend in cyclone frequency, also evident during the cold season, with the greatest increases during November and December.

Analysis of changes in mean annual *Hs* at offshore buoys supports the northward shift in storm tracks, although there are several possible interpretations of the results. Further analysis is needed to better quantify the observed changes, primarily due to the limited length of the buoy record and the significantly large percentage of missing observations in the datasets.

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